

Optimal Design for a Hybrid Ground-Source Heat Pump

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Abstract: Although the advantages of ground-source heat pumps over their conventional alternatives make these systems a very attractive choice for air conditioning, not only for residential buildings but increasingly also for institutional and commercial buildings, a significant barrier to wider application of this technology is a high first cost. When used in cooling-dominated buildings, ground-source heat pumps that utilize vertical, closed-loop ground heat exchangers can experience performance degradation as the entering fluid temperature to the heat pump increases over time due to heat buildup in the borefield. In these cases, it is possible to displace a large portion of the system cost by installing a supplemental heat rejecter to balance the annual heat extraction from the ground. The paper presented has shown that the heat rejection of the GLHEs and the system energy consumption are approached to discuss the ground heat balance with different design procedures and control strategies through the system simulation.

Keywords: hybrid ground-source heat pump systems (HGSHPs); cooling tower; system simulation

1 INTRODUCTION

Although ground-source heat pump (GSHP) systems are recognized to be outstanding heating, cooling, and water-heating, a significant drawback to wider acceptance of the technology is a high first cost. This is especially true in cooling-dominated commercial and institution applications where the vertical closed-loop configuration is commonly preferred. As a result, the required ground-loop heat changer (GLHE) is greatly reduced if the amount between heat extracted from the ground and heat rejected into the ground was balanced.

In order to decrease the system first cost and to improve the system performance, one of the available options is a hybrid ground-source heat pump

application. Hybrid systems incorporate supplemental heat rejecters, such as cooling towers, fluid coolers, cooling ponds, or pavement heating systems, the capacity of which is typically sized so that the annual heat rejection to the ground approximately balances the annual heat extraction from the ground. However, the design of the system components also depends on the strategy used to control the supplemental heat rejecter. Therefore, a integral consideration among the size of GLHE, the capacity of the supplemental heat rejector, and the control strategy should be done .

The size of GLHE and the capacity of the cooling tower is optimally designed based on the design procedures and control strategies under the condition of the heat balance in the ground in this paper.

2 HYBRID GSHPs IN TECHNOLOGY LITERATURE

The paper is proposed to analyze the impact of supplemental heat rejecters on GSHP loop length design and annual ground heat balance. A review of recent literature on hybrid GSHP systems yielded only modest number of references to research documents. The works are summarized below.

ASHRAE (1995)[1] discusses the benefits of hybrid GSHP systems for commercial/institutional buildings considering the first cost and available surface area limitations. A design procedure is suggested for cooling-dominated buildings that estimates the capacity of the supplemental heat rejecter based on the difference between the monthly average cooling and heating loads for the building. The ground-loop heat exchanger is sized to satisfy the building's heating load and the cooling load requirement for the ground loop in excess of that of the heating load is met through supplemental heat

rejection.

Kavanaugh and Rafferty (1997) [2] discuss a few alternatives for hybrid GSHP systems ground-loop heat exchanger design. The high cost is one of the primary factors that may mandate the consideration of a hybrid system. Other considerations include limited land area, the cost of the land, or the high cost of high-efficiency heat pumps. The size of the supplemental heat rejecter is based on peak block load at the design condition. Similar to that of ASHRAE (1995), the nominal capacity is calculated based on the difference between the ground-loop heat exchanger lengths required for cooling and heating.

Kavanaugh (1998)[3] revises and extends the design procedures recommended by ASHRAE (1995) and Kavanaugh and Rafferty (1997). The revisions to the practice of hybrid ground-source heat pump system design involve balancing the heat flow to the ground on an annual basis in order to limit heat buildup in the borehole field. The annual operating hours of the supplemental heat rejecter needed to balance the heat rejection and extraction in the ground are calculated based on a set point control of the ground loop temperature (a typical range of 80°F[27 °C] to 90°F[32 °C]). The procedure is demonstrated on a multi-story office building placed in three different climatic regions. The author's results indicate that warm climates are most appropriate for the hybrid application since the savings in required bore length are much more significant than for moderate and cold climates.

Yavuzturk and Spitler (2000)[4] use a system simulation approach to compare the advantages and disadvantages of various control strategies for the operation of a hybrid GSHP using a cooling tower in a small office building. The control strategies investigated may be broadly categorized into three groups: 1) a set point control to operate the cooling tower when the heat pump entering or exiting fluid temperature exceeds a set value, 2) a differential control to operate the cooling tower when the difference between the heat pump entering or exiting temperature and the ambient wet-bulb temperature exceed a set value, and 3) a scheduled control to

decrease heat buildup in the ground by operating the cooling tower for a given period of time during the night. In general, the system simulation results showed that the most beneficial control strategies were found to be those that operate the supplemental heat rejecter primarily when heat rejection conditions are most favorable.

3 METHODOLOGIES FOR SYSTEM SIMULATION AND ANALYSIS

3.1 Building Description and Loads Calculation

An office building in Wuhan City was selected for simulation the performance of hybrid GSHP systems. The total area of five storeys building is about 3200m². The following table 1 assumptions have been done to determine the annual building loads. The office occupancy is taken as 0.2 person per m².

The schedule for work and rest is from 7:00 am to 17:00 pm. The index value descends to original 30% on the weekend.

The annual building loads are simulated using DeST—C (2000) simulation software with typical meteorological year (TMY) weather data. Considering the actual running and operation conditions, the calculated annual building loads on an hour by hour basis are shown Figure 1. The total annual building heat loads are 136158kWh while the cooling loads are 342207 kWh adopting the BIN method. Obviously, when satisfy indoor comfortable environment is satisfied, the building rejects more heat to the ground than it extract on an annual basis. The heat buildup may occur in limited heat storage capacity soil, which degrades the performance as the entering fluid temperature to the heat pump increases over time.

3.2 Operation and Control Strategies

In this present study, we adapt two control strategies as follows.

(a) The cooling tower is operated when the difference between the heat pump entering or exiting temperature and the ambient wet-bulb temperature exceed a set value and the heat pump exiting fluid temperature exceeds a set value

Tab. 1 The dominating heat index inside the building

Influence factor	Radiant heat gains (W/person)	Wet gains (kg/h)	Lighting loads (W/m ²)	Equipment loads (W/m ²)	Fresh air volume (m ³ /h)
The index value per person	64	0.084	9	20	30

(b) This control strategy is put forward mostly based on the following reasons: in the initial stages of cooling, the cooling tower operation is solely done. At the stage the outdoor temperature is not high which benefits the effective operation of the cooling tower and reduce the running time of GLHEs to recover the ground temperature. In the medium stages, both of the cooling tower and GLHEs operate for cooling. In the last stages, similarly, the cooling tower operation is solely done. The operation conditions is described below.

(c) Because the compute time in the BIN method is not continuous, the calculation is not analyzed on an hour by hour basis. It is necessary to revise the solely operation condition of GLHEs.

3.3 Ground-Loop Heat Changer and Cooling Tower Sizing

In the optimal design process of ground-loop heat changer and cooling tower(the supplemental heat rejecter), it is discovered that the capacity of cooling towers is sized after the ground loop is determined to meet the building heating loads for above-mentioned design methods. It is neglected that when the outdoors air temperature is not very high and the building cooling loads exist, the entering fluid temperature to the heat pump could lower by adopting a cooling tower. Additionally, the proper adjustment between cooling tower and GLHEs should be done to lower the entering fluid temperature to the heat pump and benefit the heat pump performance because the exiting temperature of GLHEs increase over a long running time. It is necessary that the size of cooling towers is firstly determined to avoid the performance degradation of heat pump in the field where the balance amount between the heat rejection and the heat extraction. The design procedures brought forward by the author is following.

1) According to the empirical operation data of the

heat pump, the average entering fluid temperature (T_{jp}) to heat pump in situ should be achieved.

2) The relation between the exiting fluid temperature (T_{cl}) and outdoor wet bulb temperature (T_s) is described as: $T_{cl} = T_s + 4$ (3~5) °C. The cooling towers is more beneficial to the operation efficiency of heat pump than ground loop heat exchangers when T_{cl} is less than T_{jp} under the same flux. Hence, T_s which equals to $(T_{jp} - 4)^\circ\text{C}$ is taken as the temperature balance point (T_s') of the cooling tower size.

3) According to the annual outdoor wet and dry bulb temperature on a hourly basis, the average temperature (T_g') corresponding to outdoor dry bulb temperature (T_g) is found out when T_s is equal to T_s' . The building cooling loads (Q_c') is calculated at the outdoor climatic condition.

4) According to the running parameters of the heat pump and the energy efficiency ratio (EER), the heat rejected to the ground is calculated as :

$$Q_f' = Q_c' \times \left(\frac{1}{EER} + 1 \right)$$

5) The cooling tower size is determined according.

6) The lengths required (L_c) of ground loop heat exchanger for cooling and The lengths required (L_h) of ground loop heat exchanger for heating is calculated using the design procedure commended by IGSHPA[5].

7) The GLHE lengths with supplemental cooling towers for cooling as is calculated as:

$$L_c' = \frac{Q_c - Q_c'}{Q_c} L_c$$

If L_c' is not less than L_h , the GLHE lengths equal to L_c' . Otherwise the lengths equal to L_h .

The ground and the cooling tower sizing method

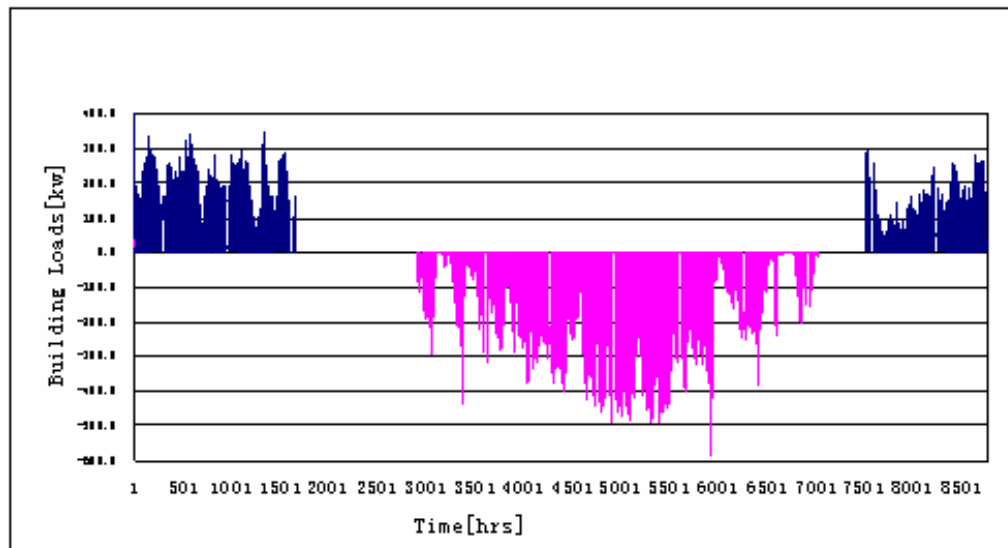


Fig. 1 Annual building loads for climatic conditions typical of wuhan(cooling load are negative and heating loads are positive)

is described below for each simulation case with different control strategies.

Case 1 (base case). For this case , the GLHEs was sized without any supplemental heat reject The average entering fluid temperature (T_{jp}) to the heat pump in wuhan city is taken as 28°C . The nominal capacity of the heat pump was 500kw for cooling and 350kw for heating. The borehole field for the base case consisted of 64 boreholes in a 8×8 configuration with a borehole depth of 73.4m and a borehole spacing of 4m.. A large loop was required because of the great cooling load The heat transfer for base case was water with a flow rate of $0.0291\text{m}^3/\text{s}$ per borehole. Undisturbed ground temperature of 17.3°C was chosen for the system simulation. Other configurations of the boreholes geometry included a constant average thermal conductivity of $2.8\text{W/m}\cdot\text{k}$ and thermal diffusivity of $1.56\times 10^{-6}\text{m}^2/\text{s}$ for the ground, a constant average thermal conductivity of $0.42\text{ W/m}\cdot\text{k}$ for the grout, borehole diameter of 0.11m, a constant average thermal conductivity of $1.0\text{ W/m}\cdot\text{k}$ and a constant fluid convective thermal conductivity of $2700\text{ W/m}^2\cdot\text{k}$ and inner diameter of 0.026m and the outer diameter of 0.032m for the U-tube pipe. Case 2,3,4,5,6. For these cases, the borehole field was reduced from 49 (7×7 configuration) boreholes to 25 (5×5 configuration) boreholes. The other configurations of the boreholes

geometry were similar to the base case. The GLHEs was sized based on the cooling tower with the nominal capacity of 244kw. Heat was rejected to the cooling tower using the differential control strategy as described above. Table 2 summarizes the length of GLHEs, the capacity of the cooling tower, and the different control strategy for each case.

4 RESULT AND DISCUSSION

Table 3 summarizes the heat rejection and the total energy consumption for each case. The details are discussed below. As analysis of the data presented in Table shows that Case 1 is the highest energy consumption alternative. It is evident the system energy consumption is mainly dominated by nothing more than GLHEs. Even though the length of GLHEs for Case 2 is small than Case 3 and Case 4, the total energy consumption and total heat rejection are obviously the highest. This is basically due to the overfull running time of GLHEs resulting in bad heat emission effect. The better energy conservation can be achieved and the heat rejection of GLHEs become less after leaving out the sole operation of GLHEs for Case 3 and Case 4.

Tab. 2 Summary of design parameters for each simulation case

Case	The Capacity of Heat pump (kW)	The length of GLHEs (m)	The flux of GLHEs (l/s)	The size of the cooling tower (kW)	The Flow Rate of The cooling Tower (l/s)	Control strategy
1	250×2	9400	29.1	0	0	
2	200+300	3800	11.7	360	17.4	a
3	200+300	5400	17.2	250	11.9	b
4	200+300	5400	17.2	250	11.9	c
5	200+300	4800	11.7	360	17.4	a
6	200+300	6800	17.2	250	11.9	c

The length of GLHEs for Case 5 and Case 6 is augmented based on Case 2 and Case 4 respectively. The energy consumption and the heat rejection amount for Case 4 is lower than that for Case 4 while the energy consumption and the heat rejection amount for Case 5 is higher than that for Case 2 . This is mainly because that even if the exiting fluid temperature of 24 from GLHEs and the outdoor wet bulb temperature of 21 arrive, the cooling tower is not in operation according to the control strategy that the cooling tower does not operate until the difference between the exiting fluid temperature from GLHEs and the outdoor wet bulb temperature is over 4 . However, if the building heat load is rejected by GLHEs together with the cooling tower, the heat rejection of GLHEs and the exiting fluid temperature decrease as well as the outcome of the combined operation is better than before. That is just the reason that the energy consumption amount and the heat rejection for Case 4 are higher than one for Case 2 as the length of GLHEs increases. The difference percentage between the heat rejected to the ground and the heat extracted from the ground is heat through different design procedures and control strategies.

2) The balance of ground heat does not depend

135.4%,71.4%,215.3% and 67.8% respectively for Case 2,4,5,6. It can be seen from the above analyses that difference between the heat rejected and the heat extracted for Case 6 is the least and the heat balance is well to benefit the ground heat recovery around the boreholes.

5. CONCLUSION

A design procedure to determine the size of a hybrid GSHP system that utilizes a cooling tower as a supplemental heat rejecter has been presented. As the design is strongly influenced by the strategy used to control the cooling tower, the most efficient control strategy from the work of Yavuzturk and Spltler is adopted for this paper. The paper presented has shown that though the system simulation the heat rejection of the GLHEs and the system energy consumption are approached to discuss the ground heat balance with different design procedures and control strategies. Some specific conclusions of this study are as follows.

1) Case 6 is most beneficial to balance the ground

on the high energy consumption and first cost using the effective control strategy.

Tab. 3 Summary of the system performance for all cases

Case	1	2	3	4	5	6
Total energy consumption (kWh)	87414.5	84693.4	79864.1	79031.4	86895.4	75313
The heat rejected (kWh)	429611	240392	185597	175050	321982	171332

3) The study presented mainly discusses the design procedures and control strategies based on the ground heat balance. A life-cycle cost analysis is not performed to evaluate the economics of the various cases that were simulated. In the future study, the optimal size GLHEs and cooling towers with corresponding control strategy can be approached until a minimum cost has been found.

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